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POSTGLACIAL FIRE, VEGETATION, AND ENVIRONMENTAL CHANGE IN THE SINLAHEKIN WILDLIFE AREA, OKANOGAN COUNTY, WASHINGTON (USA)

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POSTGLACIAL FIRE, VEGETATION, AND ENVIRONMENTAL CHANGE IN THE SINLAHEKIN WILDLIFE AREA, OKANOGAN COUNTY, WASHINGTON (USA)

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Resource Management

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by

Kevin Christopher Haydon

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CENTRAL WASHINGTON UNIVERSITY

Graduate Studies

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ABSTRACT

POSTGLACIAL FIRE, VEGETATION, AND ENVIRONMENTAL CHANGE IN THE SINLAHEKIN WILDLIFE AREA, OKANOGAN COUNTY, WASHINGTON (USA)

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Historically fire has played a key disturbance role in many ecosystems of the western United States. One of the most affected landscapes is the dry ponderosa pine-dominated forests of eastern Washington. Over the past decade, these forests have experienced a dramatic increase in large, high-severity wildfires, resulting in significant damage to natural resources, property, and habitat. Public land managers are now faced with the increasing challenge of maintaining these fire-dependent ecosystems in tandem with the projected impacts of future climate change. To do this, land managers need to make informed, adaptive decisions based on what it known in terms of historic fire regimes and how ecosystems respond to climate variability, both past and future. However, little is known about the long-term fire history of these dry forests in Washington State. The purpose of this study was to reconstruct the long term fire and vegetation history of Doheney Lake in the Sinlahekin Wildlife Area (SWA), which is located in a dry ponderosa pine forest. A 614 cm-long sediment core was recovered from the site that spanned the past ~12,210 calendar years before present. Macroscopic charcoal and pollen analysis were used to reconstruct the postglacial environmental history of the site. Results show that fire maintained a constant presence on the landscape and has been closely linked to fuel availability, until Euro American settlement (ca. AD

1850). In general, fire activity was highest during late Holocene when climate is thought to have been cool and wet, which may suggest the influence of interannual climate variability and/or the possibility that human ignitions contributed to the fire regime. Fire in the Sinlahekin Wildlife Area will likely continue to be driven by fuel availability and climate, therefore land managers may want to consider expanding their use of fire as a management tool.

ACKNOWLEDGEMENTS

I would like to express my many thanks to my friends, family, and CWU faculty for their encouragement and patience throughout this long journey. I would like to thank Dr. Megan Walsh for her willingness to accept me as a student and for sharing her subject matter expertise. I would also like to sincerely thank everyone who helped make this project possible, both in the lab and in the field. I would like to extend a special thanks to Dale Swedberg for sharing his passion for the Sinlahekin and for remaining a motivating force, even after retiring. I would also like to express my appreciation for support in the form of funding from the CWU College of the Sciences and the American Association of Geographers. Finally, I would like to say a very heartfelt thanks to my parents, Larry and Lori, and my partner, Megan Nelson. The three of you have given me the gentle, yet steady support I needed to accomplish this milestone on my timeline. Megan, you have been my anchor to sanity through times of great uncertainty and stress, right up to the final moments of this project. I am optimistic that the completion of this thesis will lead to smoother sailing for you, Kobe, Josie, and me.

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CHAPTER I

INTRODUCTION

Problem

Historically fire has played a key disturbance role in many ecosystems of the western United States (Fitzgerald, 2005). By promoting biodiversity, cycling nutrients, and maintaining spatial variability, it has been an important element across numerous landscapes (Brown et al., 2004; Peterson et al., 2005). Over the past century, active fire suppression by land managers has severely altered historic fire regimes in many forest types, some of which are now facing unnatural densities of late-successional species (Arno et al., 1997; Harrod et al., 1999). This leads to a reduction in biodiversity and reduces their resilience to natural disturbance agents like fires and insect outbreaks (Agee, 1993; Peterson et al., 2005).

One of the most affected landscapes is the dry ponderosa pine (*Pinus ponderosa*)-dominated forests of eastern Washington (Fitzgerald, 2005). Over the past decade, these forests have experienced a dramatic increase in large, high-severity wildfires, resulting in significant damage to natural resources, property, and habitat (Graham and Jain, 2005; Dale, 2009). The 2015 fire season in Washington is evidence of this, which marked the worst wildfire season in state history with over one million acres burned, 250 homes lost, an $89 million bill to taxpayers, and three firefighter fatalities (WaDNR, 2017). Public land managers are now faced with the increasing challenge of maintaining these fire-dependent ecosystems in tandem with the projected impacts of future climate change (Covington et al., 1997; Fitzgerald, 2005). To do this, land managers need to make informed, adaptive decisions based on what it known in terms of historic fire regimes and how ecosystems respond to climate variability, both past and future (Harrod et al., 1999; Hessburg et al., 1999).

Little is known about the long-term fire history of these dry forests in Washington State. Previous studies based on the analysis of fire-scarred trees have shown that the ponderosa pine/Douglas-fir (*Pseudotsuga menziesii*) forests of the eastern Cascades were characterized by short return intervals and low-intensity fires prior to Euro American settlement (Hessburg et al., 1999; Everett et al., 2000; Ohlson and Schellhaas, 2000). Wright and Agee (2004) found mean fire return intervals for the past ~400 years of 18.8 years the Teanaway River drainage near Ellensburg. Everett et al. (2000) showed average fire free intervals of 6.6-7 years from AD 1700-1860 for the Mud Creek drainage near Entiat and the Nile Creek Drainage near Naches. Research conducted in the Sinlahekin Wildlife Area near Tonasket by Schellhaas et al. (2000) found that mean fire free intervals in two units were 6.1 years and 8.5 years from 1792-1896 and 1768-1896, respectively. While these records provide insight into fire activity from the pre-settlement era, they lack the length necessary to illustrate how past fire regimes varied in relation to climatic and vegetation shifts in these ecosystems on longer timescales. A record spanning several thousand years will allow land managers to better understand these past relationships, and better prepare these ecosystems for future climate change.

Purpose

The purpose of this study was to reconstruct the long term fire and vegetation history in one portion of ponderosa pine forest in the Eastern Cascades/Okanogan Highlands with the goal of better understanding how and why long term fire activity has varied during the postglacial period. The area chosen for this research was the Sinlahekin Wildlife Area (SWA), which is the oldest wildlife area in the state and comprises predominantly of eastern slope dry forest types and sagebrush steppe communities (Franklin and Dyrness, 1988). This area is ideal for this study because of the well documented history of land use actions and management strategies (including fire suppression), previously conducted tree ring-based fire studies, and a recent increase in fire occurrence. Additionally, area land managers have shown interest in using long term paleoecological records and the data they reveal as a means to support the use of fire in future land management strategies (WDFW, 2006). The specific objectives of this research were as follows.

1) To reconstruct the postglacial fire and vegetation history of the SWA using macroscopic charcoal and pollen analysis of a lake sediment core.

During summer of 2011, sediment cores spanning the past ~12,000 years were recovered from Doheney Lake and Blue Lake in the Sinlahekin Wildlife Area. Magnetic susceptibility, loss-on-ignition, and macroscopic charcoal techniques were used to analyze both cores, and pollen analysis was conducted on the Doheney Lake core. Radiocarbon dates along with the presence of known tephra layers were used to create an age-depth model for each core. However, because of abnormalities in the Blue Lake core likely caused by multiple mass wasting events in the watershed, indicated by both the charcoal and magnetic susceptibility records, only the Doheney Lake core was analyzed further using the CharAnalysis statistical program, and is described in the following manuscript.

2) To examine how postglacial climate variability, climate-driven vegetation shifts, and human land use activities influenced past fire activity at the site.

In order to examine these influences, the Doheney Lake record was interpreted within the context of what is known in terms of climatic changes during the past ~12,000 in this area of the PNW. In addition, the reconstructed fire and vegetation history was placed into the larger regional context by comparing it with available nearby paleoenvironmental records, as well as the combined record for the PNW. This allowed for some distinction between localized versus regional influences on the record. Lastly, the Doheney Lake reconstruction was interpreted within the context of what is known about pre-contact human history and their impacts on the landscape in this area of the Eastern Cascades during the postglacial period.

3) To determine the extent to which pre- versus post-settlement fire regimes and vegetation patterns differ in the SWA and the implications of this for future forest management.

To achieve this, the high-resolution short term dendrochronological records from the Sinlahekin Wildlife Area were examined alongside the reconstructed fire and vegetation histories from Doheney Lake. Euro American settlement patterns and area land management strategies were also considered.

Significance

This research is significant for many reasons. First, the SWA is the oldest wildlife area in the state of Washington. It was established in 1939 and is currently under the joint ownership of the United States Bureau of Land Management, Washington Department of Natural Resources, and the Washington Department of Fish and Wildlife. The SWA is located in the Ponderosa Pine Zone and supports high levels of biodiversity which includes over 510 species of vascular plants, 210 species of birds, 60 species of mammals, 25 species of fish, and 20 species of reptiles (WDFW, 2018). The current management has expressed interest in reconstructing the long-term fire history of the SWA to use as a reference for prescribed burning (WDFW, 2010). However, prior to this study no data existed addressing the long-term fire history of ponderosa pine forests on the eastern slope of the Cascade Range.

The results of this study will add data to the existing body of literature regarding linkages between fire regimes, vegetation, and climate change in the PNW. These data may be examined with already existing data from the PNW in order to conduct a comparative study on the regional synchronicity of fire regimes (Walsh et al., 2015). These data may also be a valuable resource for land managers in the formulation of future management plans when coupled with projected climate change. These data will serve as a long term record of the role of fire in forest ecosystems and may be useful in informing the public of the crucial role fire has historically played in maintaining these forests throughout the postglacial period.

CHAPTER II

LITERATURE REVIEW

Ponderosa Pine Forests of the Eastern Cascades

Historical Context

Throughout history, ponderosa pine forests have served as a valuable natural resource for wildlife and humans, and they and continue to maintain their importance today (Oliver and Ryker, 1990). Currently they support a wide array of ecological, economic, and recreational functions (Graham and Jain, 2005). In order to prepare these forests for projected climate change, it is necessary to evaluate their current state along with their environmental history (Whitlock and Bartlein, 2004; McKenzie et al., 2000). Through a better understanding of these forests and the natural processes that shape and maintain them, land managers will be better equipped ensure that they remain viable for future generations (Whitlock et al., 2003; Kolb et al., 2007).

Distribution and Ecology

Ponderosa pine forests are distributed widely throughout the Pacific Northwest, including portions of Washington, Oregon, Montana, and Idaho (Graham and Jain, 2005). In eastern Washington, ponderosa pine forest is found in a small band varying from 15 to 30 kilometers wide along the eastern flank of the Cascade Range and extensively in the Okanogan Highlands Province located in the north-central part of the state (Franklin and Dyrness, 1988). In these areas, the forests generally span an elevation of 600 to 1,200 meters above sea level. Ponderosa pine, which is the dominant tree within the ponderosa pine zone, is a large evergreen conifer found throughout the western United States. Its distribution stretches as far north as British Columbia and as far south as Mexico (Graham and Jain, 2005).

According to Oliver and Ryker (1990), ponderosa pine forests occur in a wide range of soils. These soils may be derivatives of igneous, metamorphic, or sedimentary rocks. Common parent material for soils where ponderosa pines are found include quartzite, schist, basalt, granite, lime stone, and sandstone. These soils fall into the alfisols, entisols, inceptisols, mollisols, and ultisols orders. Franklin and Dyrness (1988) note that in eastern Washington, coarse-textured sandy soils produce ponderosa pine with higher growth and survival rates when compared to those found in areas with fine-textured clayey soils. Concentration of soil nutrients such as nitrogen (>.9 percent) and phosphorus (>.08 percent) necessary for ponderosa pine growth are low when compared to amounts required to support other conifers with overlapping ranges (Oliver and Ryker, 1990).

The typical growing season for ponderosa pine east of the Cascades in Washington consists of a hot summer with little precipitation; July, August, and September often receive less than 25 millimeters total (Franklin and Dyrness, 1988). Winters are characterized by low temperatures and considerable precipitation with total annual precipitation is generally between 355 and 760 millimeters, much of which comes in the form of snow (Franklin and Dyrness, 1988). Summer thunderstorms are frequent, and lightning strikes often ignite dry fuels during drought years (Agee, 1993). These years have been noted to align with regional climatic drivers such as El Niño-Southern Oscillation and the Pacific Decadal Oscillation prior to the period of European settlement (Hessl et al., 2004). Although ponderosa pine thrives in the dry, eastern Washington environment, adequate soil moisture during spring and early summer is critical for seedling establishment (Agee, 1993).

According to Fitzgerald (2005), ponderosa pine is one of the most fire-adapted conifers of the western United States, and its morphological characteristics reflect this. Ponderosa pine develops a deep root system early on to facilitate the uptake of nutrients and water. These deep roots are less susceptible to damage caused by ground fires. Ponderosa pine also boasts thick, flakey layers of bark that fall off when burning; this is often considered their greatest fire adaptation. When mature, the bark of the tree turns a distinct reddish-orange color. Needles are bundled, typically three per fascicle, and can range from 12-28 cm. They provide protection for buds from fire. Ponderosa pine has a fairly simple branching structure, with branches often growing well off the ground. This prevents rapid spread of ground fires to the relatively open crowns (Fitzgerald, 2005). Ponderosa pine may live as long as 300-600 years. Senescent trees may reach over 70 m in height and over 2 m in diameter.

Numerous other tree species co-occur in eastern Washington ponderosa pine forests. Particularly common trees include Douglas-fir (*Pseudotsuga menziesii*), grand fir (*Abies grandis*), lodgepole pine (*Pinus contorta*) and western larch (*Larix occidentalis*), with adjacent riparian zones composed of black cottonwood (*Populus trichocarpa*), red osier dogwood (*Cornus sericea*), and quaking aspen (*Populus tremuloides*) (Franklin and Dyrness, 1988). A wide variety of forbs can also be found including balsamroot (*Balsamorhiza* spp.), sagebrush mariposa lily (*Calochortus macrocarpus*), Oregon sunshine (*Eriophyllum lanatum*), grasswidow (*Olsynium douglasii*), and Douglas' catchfly (*Silene douglasii*) (Vance, 2010). These forbs are found along with numerous grasses including Thurber’s needlegrass (*Achnatherum thurberianum*), squirreltail (*Elymus elymoides*), Idaho fescue (*Festuca idahoensis*), pine bluegrass (*Poa secunda*), and bluebunch wheatgrass (*Pseudoroegneria spicata*) (Vance, 2010). Lichens are often found hanging from branches of ponderosa pines; most common is the black tree-lichen (*Bryoria fremontii*) (Clay-Poole, 2012).

Ponderosa pine is a fairly shade-intolerant species (O’Hara, 2005). Prior to European settlement, these forests were simple in structure with an open park-like distribution, including large gaps (~15 meters) between even-aged tree patches that formed an uneven-aged canopy (see figure 2) (Agee, 1993; Hessburg et al., 2005; Harrod et al., 2007). The understory vegetation was dominated by a variety forbs and grasses. Low branches were removed by frequent low-severity ground fires which aided in maintaining gaps, and prevented the accumulation of ground litter (Schellhaas et al, 2009). Historical reconstructions suggest stand densities ranged from 49-124 trees per hectare (Fitzgerald, 2005).

Prior to European settlement, natural disturbances such as fire and insect outbreaks have been present in eastern Washington ponderosa pine forests (Agee, 1993; Everett et al., 2000). Primarily, however, fire has the dominant force in determining forest structure, removing litter and downed deadwood, and cycling nutrients into the soil, which promotes understory growth (Hessburg et al., 2005, Schellhaas et al., 2009). Prior to European settlement, these forests were dominated by frequent, low-severity fire regimes (Everett et al., 2000; Wright and Agee, 2004). Research conducted by Schellhaas et al. (2009) suggests a historic fire-free interval of ≤17 years was common (discussed below). Fires occurring after a 17 year fire-free interval tended to be higher severity

(Agee, 1993). Wright and Agee (2004) noted that evidence of large, not necessarily stand-replacing fires is also present in historical records. These events have been observed to occur in ~27 year intervals, which coincides with periods of seasonal drought, potentially linked to the El Niño-Southern Oscillation (ENSO). Research conducted by Heyerdahl et al. (2002) suggests decadal fire activity in these forests may also be linked to precipitation variation caused by the Pacific Decadal Oscillation.

According to Hessburg et al. (1994), eastern Cascade ponderosa pine forests are also adapted to disturbance in the form of insects, the most pervasive of which is the western pine beetle (*Dendroctonus brevicomis*). The pine beetle enters ponderosa pine by boring into the bark. Once inside, the adult beetles lay eggs which hatch in and turn in to larva, eventually consuming the tree's phloem until they reach maturity. This cycle can be repeated multiple times and shares a direct relationship with likelihood of tree mortality. Most susceptible were senescent trees that were unable to extrude beetles using resin. Lightning struck trees, as well as trees occurring in the high moisture-stressed interface between the ponderosa pine zone and the arid steppe, were also highly susceptible. Beetle outbreaks serve an important ecological function by cycling nutrients from weaker trees, which creates favorable conditions for saplings to establish (Miller and Keen, 1960). It has also been suggested that beetle outbreaks in stands untouched by understory fires has aided in the maintenance of low stand density.

Other biotic disturbances found in ponderosa pine forests east of the Cascade Range include the Pandora moth (*Coloradia pandora*), pine butterfly (*Neophasia menapia*), and sugar pine tortrix (*Choristoneura lambertiana*) budworm. Though these defoliators are present in ponderosa pine forests, evidence suggests that historically, they have not been the cause of unnaturally high mortality (Hessburg et al., 1994). Western dwarf mistletoe is a pervasive parasite found in ponderosa pine forests. Historically, it was slow to spread due to low tree densities, simple crown structure, and elimination by frequent low-intensity ground fire (Hessburg et al., 1994).

Current Status

Forest structure in Eastern Cascade ponderosa pine forests is no longer open and park-like. Anthropogenic fire suppression during the 20th century has allowed shade-tolerant, fire-sensitive trees, and shrubs to fill in gaps that once existed in these forests (Peterson et al., 2005). Fire suppression coupled with slow rates of decomposition has also resulted in the accumulation of surplus litter and deadwood that remain on the forest floor. Standing deadwood or snags also act as ladder fuels, increasing the likelihood of crown fires (Everett et al., 2007). In some locations, stand densities have increased by as much as 422% and range from 1235-2370 trees per hectare (Fitzgerald, 2005; Schellhaas et al., 2009).

The exclusion of fire has allowed Douglas-fir to extensively encroach into once open ponderosa pine forests. This creates high density stands with heightened stress due to moisture competition (Schellhaas et al., 2009). These circumstances create ideal conditions for high-severity fires, which were rare in ponderosa pine zones prior to fire suppression (Hessburg et al., 2005). Analysis of current stands indicate increased susceptibility to insect outbreaks, disease, stand-clearing fire events, and diseases introduced by fire-intolerant tree species due to encroachment (Agee, 1993).

Currently, eastern Cascade ponderosa pine forests are home to numerous non-native plant species. Non-native trees include Siberian elm (*Ulmus pumila*) and golden willow (*Salix alba*) (WDFW, 2006). Though Douglas-fir and grand fir have been present in ponderosa pine forests, fire exclusion has allowed them to establish in the shade of ponderosa pine and gaps (Haeuser, 2014). Non-native forbs include bull thistle (*Cirsium vulgare*), dalmatian toadflax (*Linaria dalmatica*), black medic (*Medicago lupulina*), forget-me-not (*Myosotis arvensis*), and perennial sowthistle (*Sonchus arvensis*) (WDFW 2006). Over 15 species of non-native grasses can be found including reed canarygrass (*Phalaris arundinacea*), Kentucky bluegrass (*Poa pratensis*), Japanese brome (*Bromus japonicas*), and cheatgrass (*Bromus tectorum*) (Visalli, 2003). Presence of many of these species in ponderosa pine forests is due to anthropogenic introduction, often linked to ungulate grazing.

The introduction of new forms of disturbance during the 19th and 20th centuries such as logging, development, and ungulate grazing coupled with attempts to control natural forms of disturbance have drastically altered natural disturbance regimes. Fuel surpluses created by fire suppression have shifted fire regimes to low frequency, high-intensity (often crown fires) from the natural frequent, low-intensity (ground fires) regimes (Wilson and Baker, 1998). Research conducted by Everett et al. (2000) indicate that areas with pre-settlement fire free intervals of 6-7 years have been increased to 38-43 years following the 1910 fire suppression policy change. Harrod et al. (2007) attribute increased forest middle layer density of saplings and shrubs to the elongated fire return interval. Studies show that ponderosa pine forests that have missed 10-12 natural fire episodes have the surplus fuel, complex structure, and increased density and are highly susceptible to catastrophic wildfire.

Insect outbreaks in ponderosa pine forests share a relationship with fire activity. Lack of thinning from frequent, low-intensity fire results in competition-related stress. As competition for nutrients increases with density, growth and stand vigor decline. Hessburg et al. (1994) studied the relationship between ponderosa pine stands and insect outbreaks and found that even moderate increases in vegetation stocking increase stand susceptibility to beetle infestation. This susceptibility is heightened when seasonal stress factors such as drought are introduced. Due to unnatural stand densities, western dwarf mistletoe (*Arceuthobium*) incidence has increased. Hessburg et al. (1994) estimated that western dwarf mistletoe infested 26 percent of eastern Cascade ponderosa pine.

Future Management

Management of Washington's ponderosa pine forests east of the Cascade Range is a complex task. Recent severe fire seasons have brought attention to the undesired results of nearly 100 years of fire suppression in a fire-dependent ecosystem. The recent realization of the potential effects of climate change, more specifically greater climate variability (particularly increased drought), on these anthropogenically-modified forests have sparked interest in gaining insight into the long-term interaction between climate and fire in these ecosystems (WDFW, 2010). A common thread between potential future management plans of these forests is the necessity to employ adaptive strategies that focus on multiple ecological aspects of ponderosa pine forests (Spies et al., 2010).

When using reconstructed conditions as a guide for managing forest, it is important to take into account the natural range of variability that occurs within these ecosystems. As discussed by Agee (2003), disturbance processes in ponderosa pine forests are both cyclic and stochastic. Aside from the natural range of variability, outside influences such as Native American burning, may account for unexplainable fire events (Walsh et al., in press). Agee (2003) asserts that historical range of variability should be used define landscape goals, rather than developing structure-based targets. It is projected that as climate changes ponderosa pine will encroach areas currently occupied by lodgepole pine (Graham and Jain, 2005). With increased summer drought, stand-clearing disturbance in the lower bounds of the ponderosa pine zone could allow for the expansion of the neighboring arid steppe (Kerns et al., 2011).

It is well understood that present-day ponderosa pine forests are highly susceptible to wildfires resulting from multiple factors caused by fire suppression (Agee, 1993; Everett et al., 2000; Hessburg et al., 2005; Peterson et al., 2005). To address these issues, various silviculture techniques are commonly practiced in an effort to restore these forests to a more natural state, including thinning and prescribed burning. The techniques are often performed together using reconstructed historical stand structure and composition as a guide (Harrod et al., 1999; Fitzgerald, 2005; Peterson et al., 2005). Mitchell et al. (2009) noted that while understory fuel reduction does reduce wildfire severity, the removal of the high level of understory fuel accumulation in ponderosa pine forests results in a large release of carbon, potentially greater than that released in a wildfire. Reinhardt et al. (2008) suggest that the most effective method of silviculture includes both incremental thinning and prescribed burning. They believe that repeated fuel treatments employing both methods is the only way to not only treat the existing fuels surplus, but also increase the resiliency of forests for future fire activity.

As discussed by Spies et al. (2010), current laws and policies governing forests reflect static conditions at one point in time. It has become clear that ecosystems are dynamic and share complex relationships with the world around them. To prepare ponderosa pine forests east of the Cascade Range for projected climate change it will be critical to formulate an adaptive management strategy unique to the area. Landscape level assessments will need to be done in order to formulate management plans tailored to individual areas. Funding, societal acceptance, and jurisdictional boundaries will provide great challenges in achieving this. Between research and action, management of this nature will be expensive. Allocating finances to perform preventative forestry management has historically been a low priority for the federal government. Social pressure and public support may be the best avenue to usher the allocation of federal and state funds in the direction of preventative forestry management.

Conflicting values between federal and state management will have to be overcome in order for effective management to take place. By establishing collective goals state and federal agencies can work together rather than segment connected landscapes by political boundaries. The body of knowledge exists to begin formulating adaptive management strategies that may help conserve ponderosa pine forests east of the Cascade Range. Without political, social, and financial support to modify and prepare these forests it is likely that their vast range will greatly diminish over the next century.

Fire History Reconstruction

Fire history reconstruction aims to develop a long-term understanding of fire activity in a specific area (Agee, 1993). From these histories, it is possible to observe localized changes in fire activity that may result from changes in climate, vegetation, human activity, or other environmental factors. These records are predominantly reconstructed using one of two methods, dendrochronology or charcoal analysis of lake sediment cores (Whitlock et al., 2003).

Dendrochronology typically uses increment cores removed from living trees to date specific events (Farris et al., 2010). Dates are determined by counting growth rings contained in the core and has proven useful in accurately dating individual fire events by year (Walker, 2005). This high temporal resolution record is however limited by the availability of long-lived trees. When all trees in an area die, whether by disturbance or senescence, or are removed through logging, the record is often lost. This limits dendrochronological records for an area to the availability of living or recently downed trees present on the landscape.

Charcoal analysis has been used to reconstruct fire histories on both regional and local scales extending well beyond the lifespan of living trees (Whitlock and Larsen, 2001). These records are obtained from charcoal particles contained in sediments collected from lakes or wetlands (Whitlock and Bartlein, 2004). Radiocarbon dating of organic material and identification of tephra layers allows for the establishment of sediment deposition rates and age models for lake sediment cores, making it possible to reconstruct the frequency of past fire events (Fowler et al., 1986).

There are two common methods of charcoal analysis, macroscopic and microscopic (Patterson et al., 1987). Microscopic charcoal analysis (often called pollen-slide charcoal) tallies small charcoal particles (generally <125 µm) at specific intervals within a sediment core. These particles are susceptible to transport >7 km from fire events and are used to reconstruct regional fire records (Whitlock and Bartlein, 2004). Macroscopic charcoal analysis generally tallies charcoal particles >125 µm using the wet-sieve method contiguously throughout cores. Whitlock and Larsen (2001) found particles >125 µm are generally transported <7 km, and are useful for local fire history reconstruction. Coupling charcoal records along with pollen-based vegetation reconstructions, also derived from lake sediment cores, have the potential to provide insight into past environmental conditions and interactions between fire and climate (Whitlock and Bartlein, 2004). Given our specific objectives, we have determined macroscopic charcoal analysis to be the most appropriate fire proxy method for this research.

CHAPTER III

MANUSCRIPT

The following manuscript will be submitted to the peer-reviewed journal *Canadian Journal of Forest Research*. Because of revisions made during the peer-review process, the final published manuscript will vary some from what is printed here.

Postglacial fire, vegetation, and environmental change in the Sinlahekin Wildlife Area, Okanogan County, Washington (USA)

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I. Introduction

Historically, fire has played a key disturbance role in many ecosystems of the western United States (Fitzgerald, 2005). By promoting biodiversity, cycling nutrients, and maintaining spatial variability, it has been an important element across numerous landscapes (Brown et al., 2004; Peterson et al., 2005). Over the past century, active fire suppression by land managers has severely altered historic fire regimes in many forest types, some of which are now facing unnatural densities of late-successional species (Arno et al., 1997; Harrod et al., 1999). This leads to a reduction in biodiversity and reduces their resilience to natural disturbance agents like fires and insect outbreaks (Agee, 1993; Peterson et al., 2005).

One of the most affected landscapes is the dry ponderosa pine (*Pinus ponderosa*)-dominated forests of eastern Washington (Fitzgerald, 2005). Over the past decade, these forests have experienced a dramatic increase in large, high-severity wildfires, resulting in significant damage to natural resources, property, and habitat (Graham and Jain, 2005; Dale, 2009). The 2015 fire season in Washington is evidence of this, which marked the worst wildfire season in state history with over one million acres burned, 250 homes lost, an $89 million bill to taxpayers, and three firefighter fatalities (Washington Department of Natural Resources, 2015). Public land managers are now faced with the increasing challenge of maintaining these fire-dependent ecosystems in tandem with the projected impacts of future climate change (Covington et al., 1997; Fitzgerald, 2005). To do this, land managers need to make informed, adaptive decisions based on what it known in terms of historic fire regimes and how ecosystems respond to climate variability, both past and future (Harrod et al., 1999; Hessburg et al., 1999).

Little is known about the long-term fire history of these dry forests in Washington State. Previous studies based on the analysis of fire-scarred trees have shown that the ponderosa pine/Douglas-fir forests of the eastern Cascades were characterized by short return intervals and low-intensity fires prior to Euro American settlement (Hessburg et al., 1997; Everett et al., 2000; Ohlson and Schellhaas, 2000). Wright and Agee (2004) found mean fire return intervals for the past ~400 years of 18.8 years the Teanaway River drainage near Ellensburg. Everett et al. (2000) showed average fire free intervals of 6.6-7 years from AD 1700-1860 for the Mud Creek drainage near Entiat and the Nile Creek Drainage near Naches. Research conducted in the Sinlahekin Wildlife Area near Tonasket by Schellhaas et al. (2000) found that mean fire free intervals in two units were 6.1 years and 8.5 years from 1792-1896 and 1768-1896, respectively. While these records provide insight to past fire activity from the pre-settlement era, they lack the length necessary to illustrate how past fire regimes varied in relation to climatic and vegetation shifts in these ecosystems on longer timescales. A record spanning several thousand years will allow land managers to better understand these past relationships, and better prepare these ecosystems for future climate change.

The purpose of this study was to reconstruct fire and vegetation history in one portion of ponderosa pine forest in the Eastern Cascades in order to better understand how and why long term fire activity has varied during the postglacial period. The area chosen for this research was the Sinlahekin Wildlife Area (SWA), which is the oldest wildlife area in the state and comprises predominantly of eastern slope dry forest types and sagebrush steppe communities (Franklin and Dyrness, 1988). This area is ideal for this study because of the well documented history of land use actions, management strategies (including fire suppression), previously conducted tree ring based fire studies, and a recent increase in fire occurrence. Additionally, area land managers have shown interest in using long-term paleoecological records and the data they reveal as a means to support the use of fire in future land management strategies (WDFW, 2006).

The specific objectives of this research were: 1) to reconstruct the postglacial fire and vegetation history of the SWA using macroscopic charcoal and pollen analysis of a lake sediment core, 2) to examine how postglacial climate variability, climate-driven vegetation shifts, and human land use activities influenced past fire activity at the site, and 3) to determine the extent to which pre- versus post-settlement fire regimes and vegetation patterns differ in the SWA and the implications of this for future forest management. The paleoenvironmental record developed here will be compared with a previously reconstructed late Holocene record from the SWA, as well as other nearby records. This research is significant in that it is the only Holocene-length combined fire and vegetation record from the dry ponderosa pine forests of the Eastern Cascade Range of Washington to date. In addition, this record will contribute to the ongoing assessment of fire activity in the PNW as a whole, which is lacking in long-term fire reconstructions from east of the Cascade crest (Walsh et al., 2015).

II. Study Area

a. Background

The Sinlahekin Wildlife Area (SWA) lies on the eastern flank of the North Cascade Range in Okanogan County, WA. It is located approximately 8 km south of Loomis, WA, and approximately 16 km west of Tonasket, WA (Fig. 1). The specific location is between 48°47’26.91” and 48°36’15.52” N latitude and 119°38’11.12° and 119°43’0.33° W longitude, with elevations ranging from 475 m to just over 1,220 m. The wildlife area is situated on the western edge of the Okanogan Highlands Province and is mostly composed of the Sinlahekin Valley, a 20 kilometer long U-shaped valley of north-south orientation. The rock walls of the Sinlahekin Valley rise steeply from the valley floor, with the overall width ranging from 1.5 to 2.5 km. This dramatic topography was created by the repeated advance and retreat of the Okanogan Lobe of the Cordilleran Ice Sheet, which most recently retreated ~14,000 years ago following the last glacial maximum (Lesemann and Brennand, 2009). The current climate of the SWA is characterized by hot, dry summers and cool, wet winters, with a considerable amount of

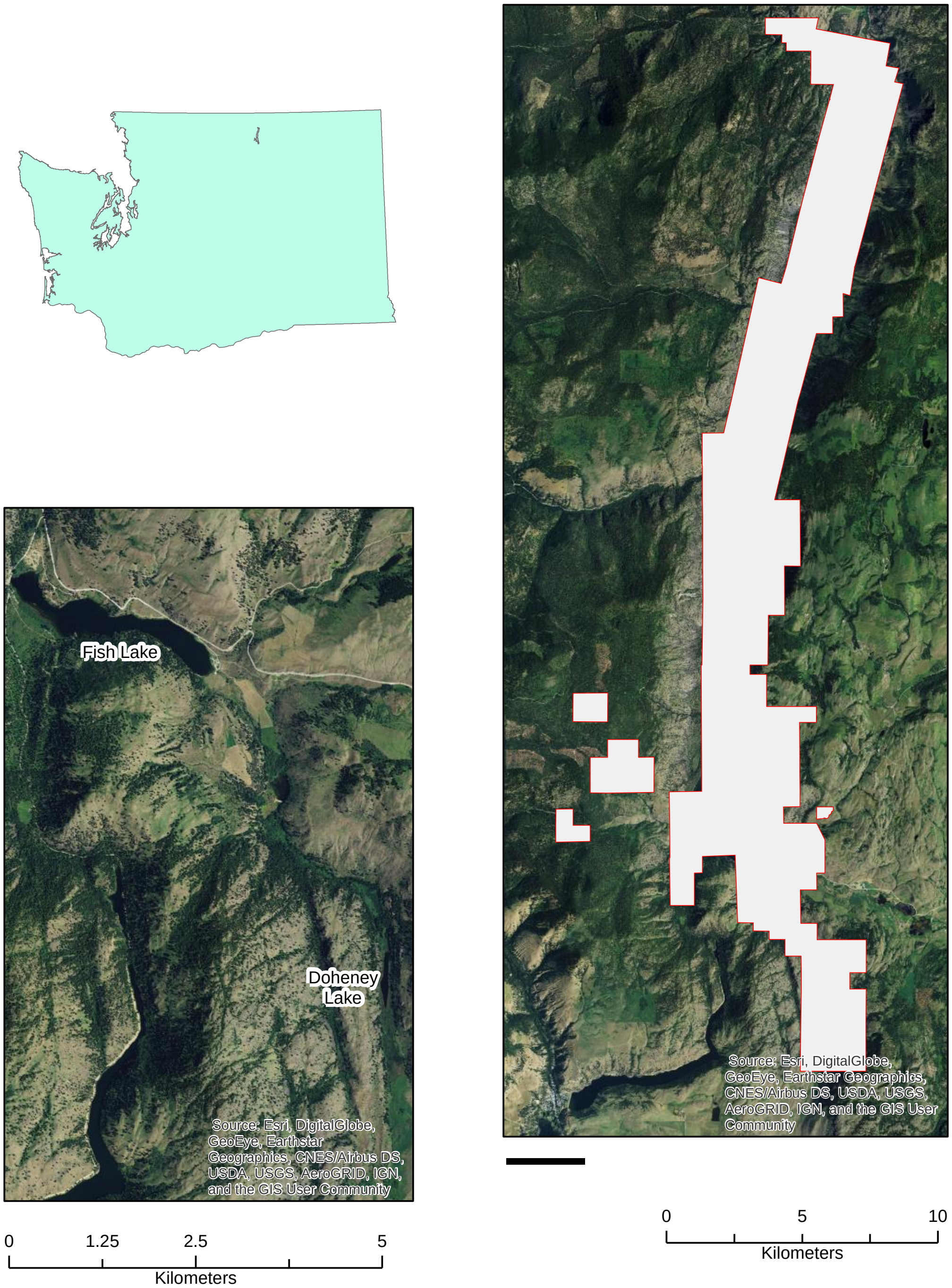

Fig. 1. Map showing the location of study site Doheney Lake and nearby Fish Lake, and the boundary of the Sinlahekin Wildlife Area (red line).

the annual precipitation arriving as snow between the months of November-March (WRCC, 2018). Summer thunderstorms are frequent and lightning strikes are often a source of ignition for dry fuels (Agee, 1994). Lightning-fire data show the nearby Okanogan National Forest has the highest ignition rate annually (35 lightning-ignited fires/400,000 ha/year) of the national forests in Washington (Kay, 2008).

The 5,800 ha SWA consists of land owned by the Bureau of Land Management, Washington Department of Natural Resources, and the Washington Department of Fish and Wildlife (WDFW); management has been assigned to WDFW. The SWA is bordered by the Loomis State Forest to the west, the Okanogan National Forest to the south, and private land to the north and east. The SWA is boasts a high level of biodiversity and is used for many recreational purposes including hunting, fishing, camping, and hiking. Numerous microenvironments in the SWA support a wide array of flora and fauna. Over 510 species of vascular plants, nine of which are rare or threatened, can be found there (Visalli, 2003). The dry forests found within the SWA are dominated by the conifers ponderosa pine and Douglas-fir (*Pseudotsuga menziesii*), with lesser amounts of western larch (*Larix occidentalis*), and numerous hardwoods primarily found in riparian locations. These dry forests, along with the lakes, rivers, and shrub-steppe of the SWA, provide habitat for 210 species of birds, 90 species of butterflies, 60 species of mammals, 25 species of fish, and 20 species of reptiles (WDFW, 2018).

b. Study Site

The study site selected for this research, Doheney Lake, is situated in the southwestern portion of the Sinlahekin Valley at 48°35’05.42” N, 119°39’52.95” W (Fig.

1). This lake is one of the few within the SWA that has not been affected by mass wasting events or altered by human land use during the late 19th and 20th centuries. Doheney Lake covers roughly four ha and sits at an elevation of 475 m, with Schalow Mountain rising sharply to an elevation 1,160 m immediately to the west (Fig. 2). The lake is roughly 580 m-long and 110 m-wide. On average, the Doheney Lake area receives 361 mm of precipitation annually, with a mean high temperature in July of 19.9°C, and a mean low temperature in December of -4.2°C (PRISM, 2018). Inflow comes from the north via Coulee Creek, while outflow occurs at the southern tip of the lake as Coulee Creek continues south. Maximum water depth is 7 meters and is found near the center of the lake. Vegetation found in the immediate vicinity of the lake includes ponderosa pine, Douglas-fir, water birch (*Betula occidentalis*), red osier dogwood (*Cornus stolonifera*), snowberry (*Symphoricarpos albus*), nootka rose (*Rosa nutkana*), Lewis' mockorange (*Philadelphus lewisii*), Douglas maple (*Acer glabrum douglasii*), ocean spray (*Holodiscus discolor*), bitterbrush (*Purshia tridentata*), wax currant (*Ribes cereum*), western serviceberry (*Amelanchier alnifolia alnifolia*), poison ivy (*Toxicodendron diversiloba*), yellow lady slipper orchid *(Cypripedium pubescens)*, and various rushes (*Juncus*) and grasses (Poaceae).

III. Methods

Fieldwork

In summer 2011, a 6.44 m-long sediment core (DL11B) was extracted from Doheney Lake at a depth of 7.0 m using a hand-powered modified Livingstone piston

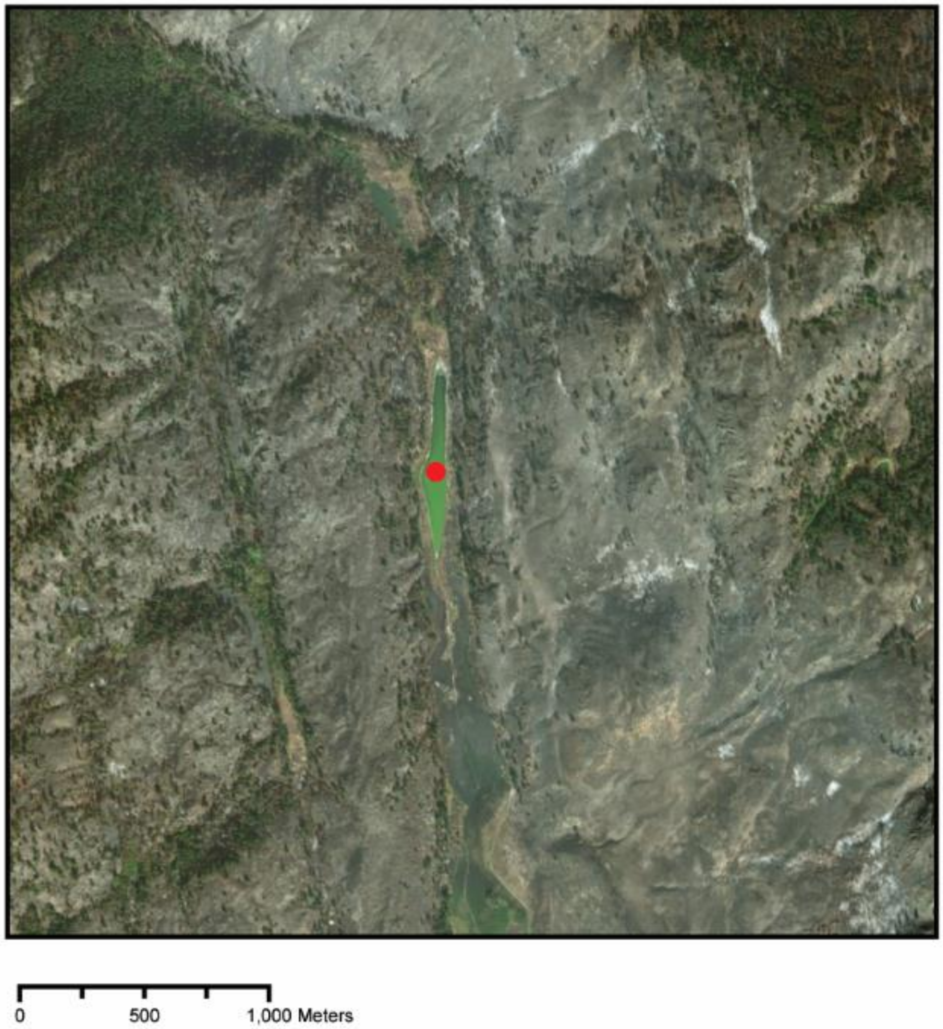

Fig. 2. Air photo of Doheney Lake and the surrounding landscape (north is at the top of the image). Red dot indicates the coring location. Note that this image was taken in 2016 after the Okanogan Complex Fire burned the watershed of the lake. Image credit: NAIP (2017).

corer (Wright et al., 1983). Core segments up to 1 m-long were extruded and described in the field, wrapped in plastic wrap and aluminum foil, and encased in split PVC pipe for transport. A .64 m-long short sediment core (DL11A) containing the sediment-water interface was also recovered using a hand-powered Bolivia piston corer. This core was sampled in the field at 1-cm intervals and placed in Whirl-pak bags. All sediment samples were transported to the Paleoecology Lab at Central Washington University where they were refrigerated.

Lab Analysis

In the lab, magnetic susceptibility analysis was used to determine the amount of magnetically enhanceable matter within the core (Thompson and Oldfield, 1986). Higher magnetic susceptibility values were interpreted as higher clastic input, indicative of allochthonous material (i.e., sediment originating outside the lake), from events such as mass movements, which often follow fire events, or from the deposition of tephra layers (i.e., volcanic ash). Lower magnetic susceptibility values were interpreted as lower clastic input, indicative of more autochthonous material (i.e., organic matter originating in the lake). Magnetic susceptibility was completed using a Sapphire Instruments 5-cm ring sampler. Readings were taken at contiguous 1-cm intervals for the entire length of the long core. Core DL11B was then split longitudinally and described based on lithological changes using the Munsell soil color chart. Organic macrofossils (e.g., needles, twigs, cones) were removed, labeled, and placed storage vials to be used for ^{14}C dating analysis.

Loss-on-ignition analysis was conducted to determine the percent organic and carbonate content of the cores (Dean, 1974). The results were interpreted as changing conditions within the lake itself and outside factors (i.e., changing amounts of surrounding vegetation, tephra deposition) contributing to lake sediment composition (Dearing, 1991). Samples of 1 cm^3 were taken at 5-cm intervals and placed in crucibles and weighed, and then dried at overnight at 90°C. The samples were then heated at 550°C and 900°C for 2 hours each time, and weight loss from each firing was used to determine the percentages of organic and carbonate material using formulas in Heiri et al. (2001).

Macroscopic charcoal analysis was used to reconstruct the fire history of the Doheney Lake watershed and followed methods described by Whitlock and Larsen (2001) and modified by Walsh et al. (2008). Samples of 2 cm^3 were taken at contiguous 1 cm-intervals using a modified syringe. Samples were placed into 7 ml vials and ~5 ml of a solution of 5% sodium hexametaphosphate was added to each vial and left for a minimum of 24 hours to deflocculate the sediment. Approximately 10 mL of sodium hyperchlorite (commercial bleach) was then added to samples and they were allowed to sit overnight. Samples were wet sieved through 125-μm and 250-μm screens; only charcoal particles >125 μm were counted because studies show that these particles travel <7 km and are therefore indicative of local fire history (Whitlock and Anderson, 2003). The remaining residue in the screens was transferred to a gridded petri dish for counting using a stereoscope at 10-40X magnification. Wood and grass charcoal morphotypes were identified and tallied separately based on published images and descriptions (Walsh et al., 2008, 2010b, in press).

Charcoal counts were entered into the program CharAnalysis for statistical analysis (Higuera et al., 2009). CharAnalysis distinguishes peaks in charcoal (i.e., fire episodes) from more slowly varying background charcoal, is able to calculate the number of fire episodes per 1000 year period, mean fire return intervals, and peak fire episode magnitudes. It is important to note that given the sedimentation rate of certain cores and the "peakiness" of a record, an identified fire episode could contain more than one fire event within it (Long et al., 1998). The charcoal concentration data were interpolated to even 20-year intervals, which represents the median resolution of the record, to create the CHAR time series. A robust Lowess smoother was used to identify the peaks from the background charcoal using a window width of 600 years. 600 years was selected after testing the sensitivity of the record to windows of 400-1,000 years, which maximized the global signal to noise index (SNI) at 3.68.

Pollen processing followed standard protocol outlined in Faegri et al. (1989). Samples of 1 cm^3 were taken at 20 cm-intervals throughout the length of the long core (DL11B). 300-500 pollen grains were counted per sample at a magnification of 400-1000X. Identifications were made to the lowest possible taxonomic level and were based on published references and the Central Washington University pollen reference collection. The exotic spore *Lycopodium* was added to the samples and tallied so that total pollen accumulation rates (PARs) could be calculated. Pollen percentages were calculated using only the total terrestrial pollen and spores counted in each sample. Aquatic sums were calculated using the entire pollen and spore sum. An openness ratio was calculated by dividing the sum of *Pinus*, *Pseudotsuga/Larix*, and *Abies* by the sum of those three taxa plus *Artemisia*, Poaceae, and Cyperaceae. Higher values indicate a more closed landscape dominated by trees, while lower values indicate a more open landscape with higher percentages of herbaceous taxa.

IV. Results

DL11B

Lithology, Charcoal Concentration, Loss-on-Ignition, and Magnetic Susceptibility

The majority of the DL11B core is comprised of fine to medium gyttja and clayey gyttja ranging widely in color, with multiple clay and tephra layers of varying thickness scattered throughout. From bottom of the core to the Mount Mazama-O tephra (292-327 cm), the core consisted primarily of clay/clayey gyttja of varying shades of blue-gray, green, and brown. A coarse sand layer occurs at a depth of 624-625 cm. A 6 cm-thick black clay layer is found from 442-448 cm, with periodic smaller clay bands found above that. Above the Mazama-O tephra to a depth of 165 cm, the sediment is medium gyttja varying in color from light to dark brown, with several more thin clay bands present. At a depth of 110-165 cm, the sediment shows laminated bands of alternating light and dark brown fine gyttja. Above that the sediment is dark brown fine gyttja, until a tephra layer identified as Mount St. Helens-W (MSH-W) is found at a depth of 62-67 cm (Nelson et al., 2011; Walsh et al., in press). Fine gyttja ranging in color from tan to dark brown is found above that to the top of the core.

Charcoal concentrations fluctuate widely throughout the record (Fig. 3). From the beginning of the record through the Mazama-O ash layer, charcoal concentrations are generally low. The average total charcoal concentration for this period is 6.14 particles/cm^3, with an average herbaceous charcoal concentration of 4.48 particlescm^3.

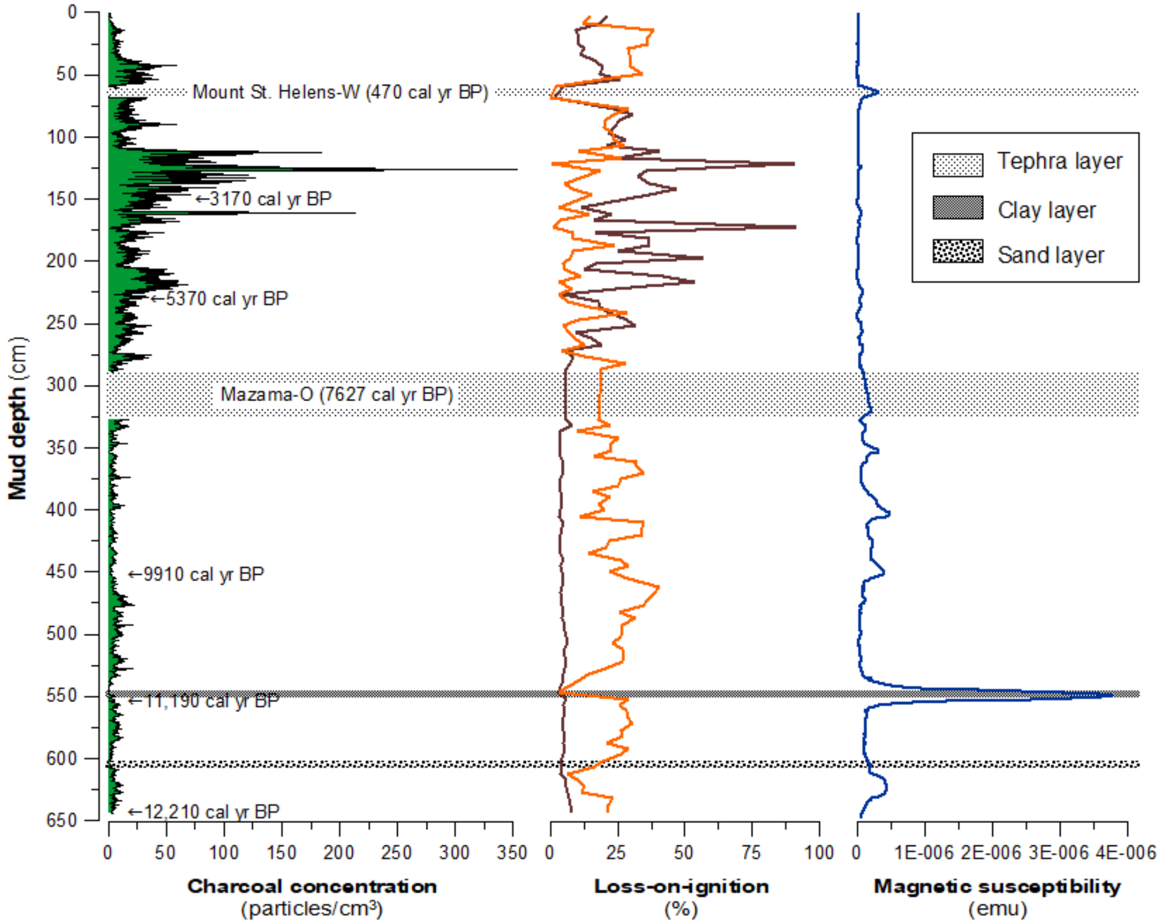

Fig. 3. Charcoal concentration (particles/cm^3; herbaceous charcoal=green curve, total charcoal=black curve), loss-on-ignition (% organics=brown curve; % carbonates=orange curve), and magnetic susceptibility for the DL11B core plotted against mud depth (cm).

Herbaceous charcoal comprises 73.0% of the total charcoal for this period. Charcoal concentrations are highest from the Mazama-O ash layer to the MSH-W ash layer. The average total charcoal concentration for this period is 34.92 particles/cm^3, with an average herbaceous concentration of 21.43 particles/cm^3. Though the average charcoal concentration is higher during this period, the average percentage of herbaceous charcoal declines to 61.4% of the total charcoal. From the MSH-W ash layer to the top of the core, average charcoal concentration declines to 13.26 particles/cm^3. Most notably during this period, the average herbaceous concentration drops to 7.59 particles/cm^3 and the average herbaceous percentage drops to 57.2%.

Loss-on-ignition values for carbonates and organics vary greatly. From the bottom of the core to the Mazama-O ash layer values for organics are consistently low and generally remain below 10%, while carbonate values are considerably higher at around 25%. From the Mazama-O ash layer to the MSH-W ash layer, percent organic values increase dramatically with peaks as high as 91%, while percent carbonate values decrease slightly to around 15%. From the MSH-W ash layer to the top of the core, percent organic values decrease to around 15% and percent carbonate values increase to around 30%. In general, the percent organic values very closely matched the pattern of the charcoal concentration curve.

Magnetic susceptibility values are generally low throughout the core, however there are a few notable exceptions. The largest magnetic peak occurs between the bottom of the core and the Mount Mazama-O ash layer at a depth of 448 cm in association with a large black clay layer (~6 cm thick). Several other smaller peaks also occur within this section of the core in association with thinner clay layers. A smaller magnetic peak occurs during the Mazama tephra layer between 292-327 cm. From the Mazama-O ash layer to the MSH-W ash layer, values remain low and consistent. A notable peak coincides with the MSH-W ash layer at a depth of 62-67 cm. From this ash layer to the top of the core no other peaks occur and values remain low.

Core DL11C

Chronology

The top 14 cm of DL11A, which was entirely brown fine gyttja, was combined with the DL11B long core using stratigraphic markers present in both cores. The combined core, hereafter referred to as DL11C, was a total of 614 cm after tephra layers were removed (it is assumed these are instantaneous events). An age-depth model was created for DL11C using five AMS ^{14}C age determinations along with the age of the MSH-W (470 cal yr BP; Mullineaux, 1986) and Mount Mazama-O (7627 cal yr BP; Zdanowicz et al., 1999) eruptions (Fig. 4). All ^{14}C determinations were the converted to calendar years before present (cal yr BP) using the Calib version 7.1 program (Stuiver et al., 2018). Ages were chosen by selected the highest value adjacent to the median age, if the median age fell in a trough on the probability distribution function; if not the median age was used. All ages were rounded to the nearest decade (see Table 1 for age determinations). As a result, the age model suggests a basal date of 12210 cal yr BP for the DL11C core with a mean sample resolution of 20 yr/cm

The sedimentation rate of core DL11C decreases slightly during the early Holocene (ca. 12200-8000 cal yr BP). During this time the average sedimentation rate was .075 cm/yr. During the first thousand years of the middle Holocene (ca. 8000-7000

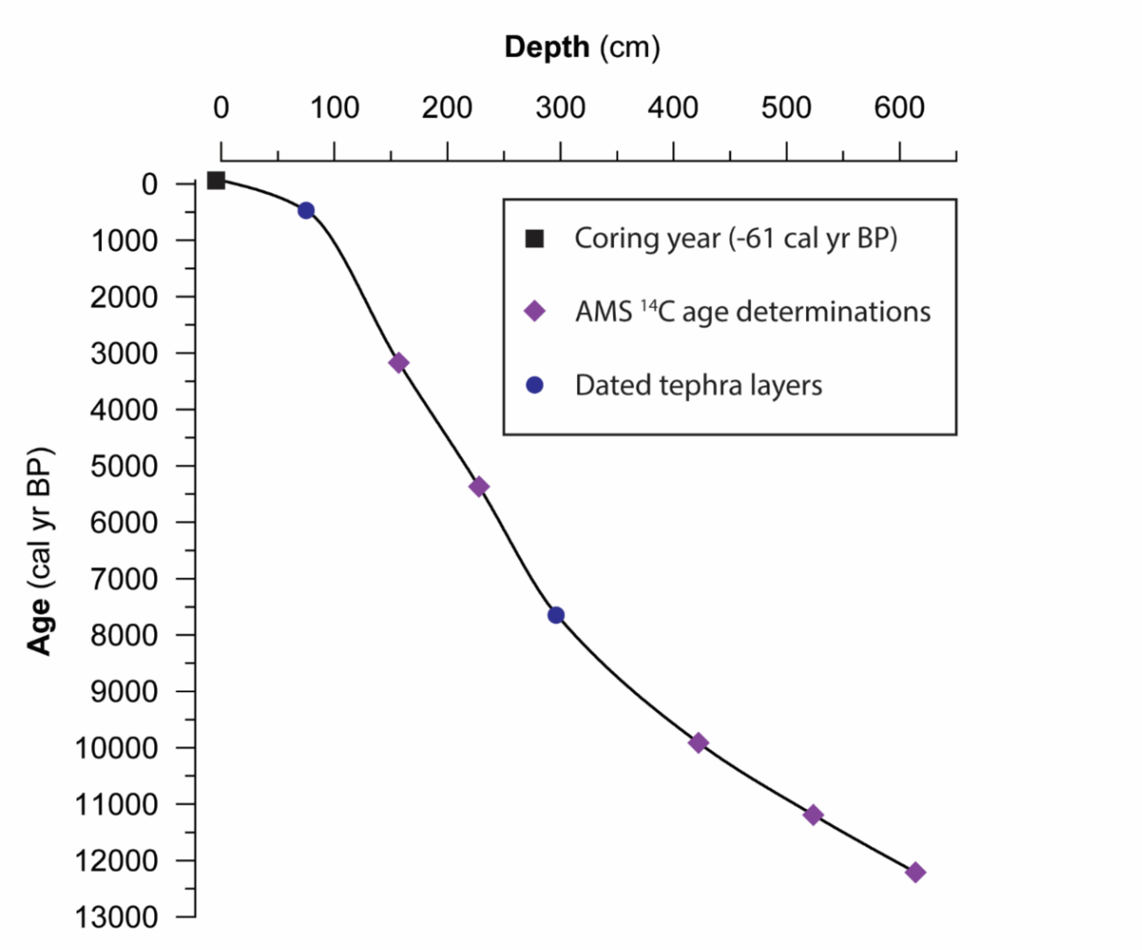

Fig. 4. Doheney Lake age-depth model for core DL11B. See Table 1 for age determinations.

Table 1. Age-depth relations for the combined Doheney Lake core (DL11C).

Depth (cm)	Lab number	Source material/ tephra layer	Measured ^{14}C age and error[a]	Calibrated age (cal yr BP)
75	-	MSH-W	-	470[b]
157	D-AMS 025189	Lake sediment	2785 +/-70	3170 (2966-3352)[c]
228	D-AMS 002841	Twig	4703 +/-31	5370 (5321-5579)
296	-	Mazama-O	-	7627[d]
422	D-AMS 003284	Wood	8843 +/-36	9910 (9742-10155)
524	D-AMS 004899	Lake sediment	9712 +/-48	11190 (10826-11237)
614	D-AMS 025192	Lake sediment	10333 +/-70	12210 (11832-12513)

[a] AMS ^{14}C age determination completed at DirectAMS facility (Seattle).
[b] Age as reported in Mullineaux (1986).
[c] Calendar ages determined using Calib 7.1 html (Stuiver et al., 2018). Ages rounded to the nearest decade with 2σ ranges reported.
[d] Age as reported in Zdanowicz et al. (1999).

cal yr BP) the sedimentation rate continued to decline gradually until it stabilized at ~.0275 cm/yr. The average sedimentation rate during the middle Holocene (ca. 8000-4000 cal yr BP) was .033 cm/yr. During the late Holocene (ca. 4000 cal yr BP- present) the sedimentation rate remained stable until about 1200 cal yr BP where it began to increase sharply for the remainder of the record. The average sedimentation rate for the late Holocene period was .081 cm/yr.

CharAnalysis

The global SNI value for the 600 year smoothing window is 3.68, indicating that overall the record exceeds the established threshold for using CharAnalysis to analyze the charcoal record. However, there were several periods during the record where it drops below 3, indicating that it is struggling to identify individual fire episodes (Kelly et al., 2011). We therefore argue that the CharAnalysis program is likely underestimating the number of fires that occurred in the watershed during the Holocene for reasons discuss below. As a result, we report the values determined by CharAnalysis; however, other indicators of fire activity (i.e., charcoal concentrations) are also reported and will be used to support our interpretation of the record.

Early Holocene (12200 − 8000 Cal Yr BP)

During the Early Holocene, the average total charcoal concentration is 5.92 particles/cm^3, while the herbaceous charcoal concentration is 4.38 particles/cm^3 (Fig. 3). Grass charcoal comprises 74.0% of the total charcoal during this period. As determined by CharAnalysis, the average charcoal accumulation rate is 0.42 particles/cm^2/yr (Fig. 5; Table 2). CharAnalysis detected 25 significant episodes with an average peak magnitude of 10.06 particles/cm^2/peak. The largest peak during this period occurs at ca. 12,020 cal yr BP and has a peak magnitude of 57.03 particles/cm^2. The average fire frequency for the early Holocene is 5.78 fire episodes/1000 yr. There is a gradual trend downward in fire frequency during this period from ~8 fire episodes/1000 yr at the start of the period to ~5 fire episodes/1000 yr by ca. 8000 cal yr BP. For the most part, the SNI stayed above three, indicating that the program was able to easily identify fire episodes during this period, with the exception of one notable dip around 9300 cal yr BP.

Table 2. Charcoal statistics for the Doheney Lake core DL11C.

	Ave. total concentration (particles/cm^3)	**Ave. herbaceous concentration** (particles/cm^3)	**Ave. CHAR** (particles/cm^2/yr)	**Fire episodes** (#)	**Ave. fire frequency** (episodes/1000 yr)	**Ave. peak magnitude** (particles/cm^2/peak)
Early Holocene (12,220-8,000 cal yr BP)	5.92	4.38	0.42	25	5.79	10.06
Middle Holocene (8,000-4,000 cal yr BP)	21.79	13.76	0.71	21	5.26	9.54
Late Holocene (4,000- -61 cal yr BP)	32.98	19.68	1.49	16	4.24	58.57

Pinus pollen dominated the entire DL11C record; however, it is found in lower percentages in this period as compared to later in the record (ave.= 41.4%) (Fig. 6). Most *Pinus* pollen was indistinguishable as either subgenus *Strobus* (white pines) or *Pinus* (yellow pines), particularly during this period, but most of what could be identified is subgenus *Pinus* (0.8%) versus *Strobus* (0.4%). Also found in relatively high percentages are *Alnus* (7.2%), *Betula* (10.9%), *Artemisia* (12.5%), Poaceae (12.9%), monolete ferns (4.5%), and *Typha* (3.1%). Several other taxa are present in low percentages, but were at their highest levels during the early Holocene including *Abies* (0.8%), *Juniperus*-type (2.6%), *Populus* (0.2%), *Sarcobatus* (0.2%), *Ceanothus* (0.3%), Amaranthaceae (excluding *Salsola*-type) (0.4%), Asteraceae (excluding *Ambrosia*-type) (0.9%), *Pteridium aquilinum*-type (0.4%), Apiaceae (excluding *Heracleum*-type) (0.3%), and other herbs. Notably, *Pseudotsuga*/*Larix* pollen does not appear in the record until ca.

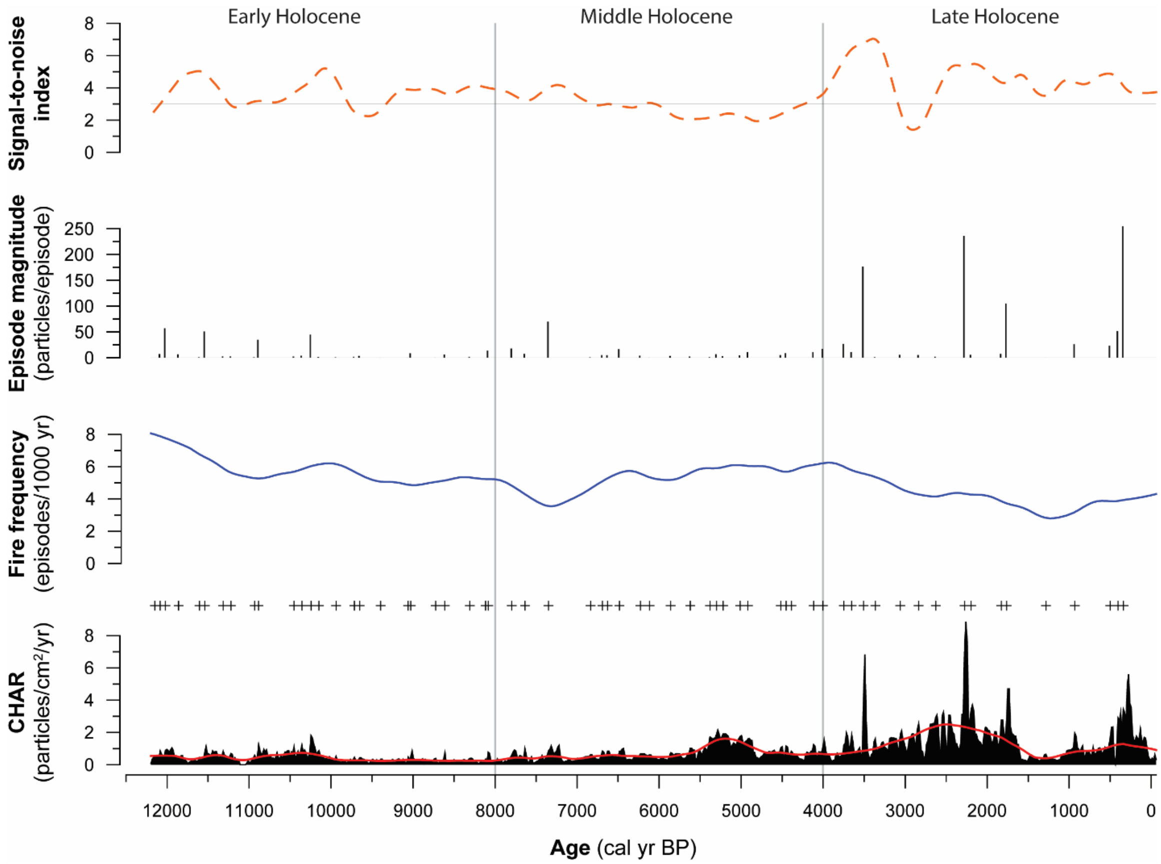

Fig. 5. Charcoal influx (CHAR; particles/cm^2/yr; red line is the background component as determined by CharAnalysis), fire episodes (plus symbols), fire frequency (# fire episodes/1000 yr; blue line), peak episode magnitudes (particles/episode; vertical bars), and signal-to-noise index (SNI; orange dashed line) plotted against age (cal yr BP) for the DL11C core.

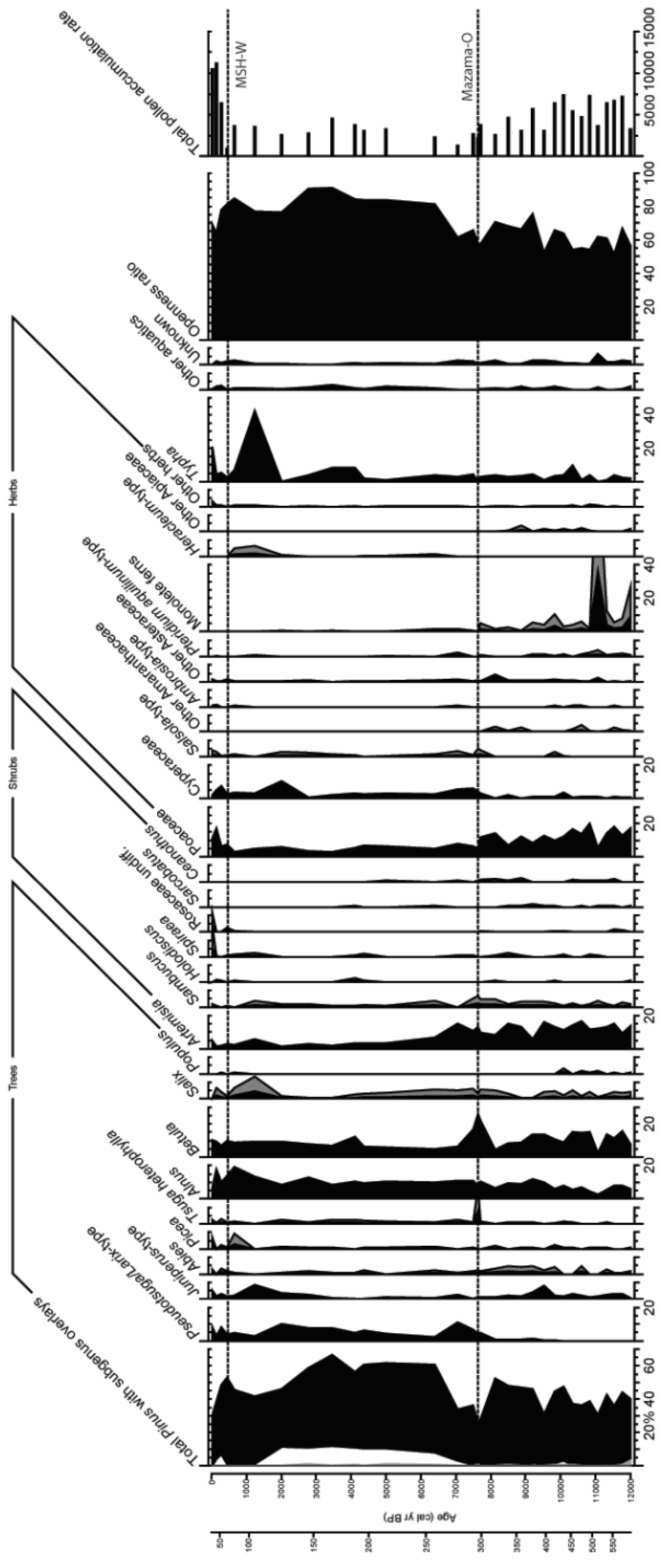

Fig. 6. Select pollen taxa percentages, total pollen accumulation rate (PARs), and tephra layers for the Doheney Lake (DL11C) core plotted against adjusted depth (cm) and age (cal yr BP). Gray shading is a 5x exaggeration of the percentage curves.

10000 cal yr BP, and then only at low levels (0.3%). The openness ratio is lowest during this period when compared to the rest of the record (0.62).

Middle Holocene (8000 − 4000 Cal Yr BP)

During the Middle Holocene, the average total charcoal concentration increases substantially to 21.79 particles/cm^3, while the herbaceous charcoal concentration increases to 13.76 particles/cm^3 (Fig. 3). Grass charcoal comprises 63.1% of the total charcoal in this period. The average charcoal accumulation rate increases to 0.71 particles/cm$^{2/}$yr (Fig. 5; Table 2). CharAnalysis detected 21 significant episodes with an average peak magnitude of 9.54 particles/cm^2/peak. The largest peak during this period occurs at ca. 7350 cal yr BP and is 70.12 particles/cm^2. The average fire frequency during this period is 5.26 fire episodes/1000 yr. Fire frequency first drops from ~5 fire episodes/1000 yr at the start of the period to ~3 fire episodes/1000 yr by ca. 7200 cal yr BP. There is then a gradual increase in fire frequency to ~5 fire episodes/1000 yr by ca. 6200 cal yr BP, after which fire frequency remains generally steady for the remainder of the period. SNI values are only slightly above the threshold of three at the beginning of the period and drop and remain below this value from ca. 6750-4000 cal yr BP, indicating CharAnalysis struggled to reliably detect fire episodes throughout much of the middle Holocene.

Pinus pollen again dominates the record with an average of 45.3% during the middle Holocene (Fig. 6). More pollen grains could be identified to the subgenus in this period, with 5.7% coming from the subgenus *Pinus* and only 0.4% coming from the subgenus *Strobus*. Also found in relatively high percentages are *Pseudotsuga*/*Larix* (5.3%), *Alnus* (9.9%), *Betula* (12.4%) and *Typha* (3.1%). Percentages of *Artemisia* and Poaceae decreased substantially from the early Holocene to 8.1% and 6.8%, respectively. However, percentages Cyperaceae increased considerably from 1.1 to 3.8%. Other taxa that occur at their highest percentages during the middle Holocene include *Tsuga heterophylla* (1.4%), *Salix* (1.4%), and *Sambucus* (1.0%). The openness ratio increases to an average of 0.72 for the period, with lower values occurring earlier in the period and higher value occurring near the end.

Late Holocene (4000 Cal Yr BP − Present)

During the Late Holocene, the average total charcoal concentration increases again to 32.98 particles/cm^3, while the herbaceous charcoal concentration increases to 19.68 particles/cm^3 (Fig. 3). Grass charcoal comprises 59.7% of the total charcoal during this period. The average charcoal accumulation rate increases substantially from the previous period to 1.49 particles/cm^2/yr (Fig. 5; Table 2). CharAnalysis detected 16 significant episodes with an average peak magnitude of 58.57 particles/cm^2/peak. The average fire frequency for the period is 4.238 fire episodes/1000 yr. The largest peak during this period occurs at ca. 340 cal yr BP and is 254.360 particles/cm^2, however, another large peak of 236.12 particles/cm^2 occurs at ca. 2280 cal yr BP. CharAnalysis suggests a gradual decrease in fire episodes during this period from ~6 fire episodes/1000 yr to ~3 fire episodes/1000 yr by ca. 1200 cal yr BP. It then increases slightly to ~4.5 fire episodes/1000 yr by the end of the record. The SNI briefly dropped to near one around 2750 cal yr BP, despite being well above three for the remainder of the period. There is a notable sharp decline in fire activity during the last ~250 years of the record, particularly after 75 cal yr BP.

Once again *Pinus* pollen dominates the DL11C record during the late Holocene with the highest average for the entire record at 47.6%, with 5.2% of the identifiable grains coming from the subgenus *Pinus* and only 0.2% from the subgenus *Strobus* (Fig. 6). *Pinus* percentages are highest near the beginning of the period at ca. 3500 cal yr BP, decrease until ca. 1200 cal yr BP, increase again until the MSH-W tephra (470 cal yr BP), and then decrease toward present. Found at their highest percentages in this zone are *Pseudotsuga*/*Larix* (6.2%), *Juniperus*-type (3.2%), *Picea* (0.8%), *Alnus* (12.2%), *Spiraea* (0.8%), Rosaceae undiff. (0.6%), Cyperaceae (4.1%), particularly after ca. 2500 cal yr BP, *Salsola*-type (0.7%-tied), *Heracleum*-type (0.4%), and *Typha* (10.4%). Several notable taxa are at their lowest percentages during the late Holocene, including *Betula* (8.7%), *Artemisia* (2.8%), *Sambucus* (0.4%), Poaceae (7.0%), *Pteridium aquilinum*-type (0.1%), and monolete ferns (0.1%). The openness ratio is on average highest during the late Holocene at 0.79. However, it is highest near the start of the period, decreases toward the middle, increases again before the MSH-W tephra layer, decreases sharply afterward, and then increases at the top of the record.

V. Discussion

Section 1: Doheney Lake Fire and Vegetation History

The age model and basal date from the DL11C core suggest that Doheney Lake formed shortly after the final retreat of the Okanogan lobe of the Cordilleran ice sheet ca. 12220 cal yr BP. The pollen record indicates that initially the vegetation at the site was an open parkland or sagebrush steppe dominated by *Pinus* (likely *P. contorta* [Mack et al., 1978c]), *Artemisia* and Poaceae (Fig. 6). This suggests a very open and dry environment, similar to what was reported by Mack (1979) at nearby Mud Lake and Bonaparte Meadows. Because of the proliferation of *Pinus* pollen and the distance it can travel, it is difficult to know whether pine trees were growing near the site or somewhere else within the watershed (Hebda and Allen, 1993). However, the openness ratio indicates that the forest was sparser at this time than at any other time during the Holocene. While CharAnalysis results indicate fires were most frequent during this period, charcoal concentrations and CHARs were at their lowest, with relatively low average peak episode magnitude, which indicates either the size, severity, or proximity of the fire to the lake (Table 2). These results coupled with the high percentage of herbaceous charcoal observed during this period suggest that the landscape around Doheney Lake was fuel-limited, and as a result, the watershed experienced frequent, low-severity fires.

The pollen reconstruction indicates substantial shifts in the vegetation near Doheney Lake early in the middle Holocene, particularly after deposition of the Mazama-O tephra layer. *Pseudotsuga/Larix* first appeared in the record ca. 10000 years ago, but remained at low levels until ca. 8000 cal yr BP. It is difficult to know whether this is Douglas-fir, western larch, or both, given that both occur in the SWA today; however, Douglas-fir is much more common (Visalli, 2010). Both taxa are well known pollen underproducers (Baker, 1976; Mack et al., 1978a), so higher *Pseudotsuga/Larix* abundance within the record at this time suggests its presence within the watershed and likely in the immediate vicinity of the lake. Concurrent with this increase is a decline in *Betula*, *Artemisia*, *Sambucus*, *Sarcobatus*, *Ceanothus*, and Poaceae, as well as most herbaceous species that were relatively abundant during the early Holocene. *Pinus,* which was in decline at the end of the early Holocene, remained low after the Mazama eruption, but then increased to near its highest abundance of the Holocene by ca. 7000-6500 cal yr BP. This increase was accompanied by an increase in grains that could be identified as the subgenus *Pinus*, likely indicating the arrival of *P. ponderosa* at the site, which is the dominant tree at Doheney Lake today. Overall these changes seem to indicate the establishment of the modern-day forests within the watershed. This is somewhat later than what was reported by Mack (1979) at Bonaparte Meadows (5000 ^{14}C years [ca. 5800 cal yr BP]); however, this site is slightly farther north than Doheney, which could account for the difference in the timing, or perhaps this is explained by more precise radiocarbon dating techniques that have developed in the past 30 years.

Accompanying this shift in vegetation at Doheney Lake during the middle Holocene are changes in fire activity. Average charcoal concentration and CHAR increased considerably as compared to earlier; however, CharAnalysis identified fewer fire episodes with a slightly lower average peak episode magnitude. The increase in fire frequency at ca. 7300-6400 cal yr BP seems to have occurred in response to the vegetation shifts noted above, which likely provided greater fuel abundance to sustain more frequent but smaller/less severe fires. It is worth noting that for nearly half of this period CharAnalysis was unable to maintain a SNI over the suggested threshold of three (Kelly et al., 2011). This brings into question CharAnalysis' ability to detect fire episodes in this portion of the record, but it is unclear whether the program is over- or under-estimating fire occurrence. Even so, the higher charcoal concentrations and CHARs in the latter part of the middle Holocene, accompanied by a smaller percentage of herbaceous charcoal observed at this time, indicates that fires were likely larger and burned more woody biomass, particularly after ca. 7000 cal yr BP.

Pinus continued to dominate at Doheney Lake throughout the late Holocene, however, its abundance greatly decreased from its highest point in the record after ca. 3500 cal yr BP. This decrease occurred simultaneous to the largest increase in charcoal concentrations and CHARs during the Holocene (ca. 3500-1600 cal yr BP). At the same time, CharAnalysis indicates that fire frequency decreased (and throughout much of the late Holocene), while peak episode magnitudes increased greatly. This, along with even lower herbaceous charcoal concentrations suggests that fires became even larger or more severe than earlier in the record and consumed a higher proportion of woody fuels. It is also possible, however, given the lower resolution of the record at this point due to slower sedimentation rates, that more fires were happening closer together in time and that multiple fire events are contained within one identified fire episode (Whitlock and Bartlein, 2004). This would result in the larger peak episode magnitudes observed during much of the late Holocene. However, the greater abundance of *Alnus* (likely *Alnus incana*) during this period suggests that fires were larger or more intense, given that it is a successional species that flourishes after fire (Fryer, 2011). As a result, the forest became more open at this time than it had been during much of the middle and late Holocene, which is supported by the openness ratio and the slightly greater abundance of *Artemisia* and *Juniperus*-type (likely *Juniperus communis*, which is intolerant of shade) (Diotte and Bergeron, 1989).

Pinus abundance increased again after ca. 1500 cal yr BP and peaked immediately following the MSH-W eruption (470 cal yr BP). This increase appears to be in response to decreased fire activity at this time, illustrated by lower charcoal concentrations, CHARs, and the lowest fire frequency of the entire record. Fire activity increased again between ca. 500-250 cal yr BP (with a notable absence in charcoal influx into the record after the MSH-W eruption) before dramatically decreasing toward present, particularly after ca. 100 cal yr BP. *Pinus* abundance then decreased toward present while other taxa increased, particularly *Pseudotsuga/Larix*, *Alnus*, *Spiraea*, Roseaceae, and Poaceae (many of which are likely invasive grasses). The only other notable vegetation change in the late Holocene suggests an increase in wetland environment and perhaps a gradual filling in of the lake, which is approaching completion at present, and is marked by an increase in particularly *Salix*, Cyperaceae, and *Typha* (including a large spike ca. 1500 cal yr BP) after ca. 3000 cal yr BP.

Section 2: Controls of Fire Activity during the Holocene

Unlike what has been documented by other paleoecological reconstructions from the PNW (Walsh et al., 2015), it seems as if fire regimes at Doheney Lake were only somewhat influenced by major climatic shifts during the postglacial period. The fire frequency curve, which often times on a millennial scale tracks changes in insolation anomaly, primarily at sites west of the crest of the Cascade Mountains (Walsh et al., 2008), does not follow this trend at Doheney Lake. Instead, fire frequency was highest at the start of the record when climate is known to have been still cold due to influence of the retreating ice sheet, and decreased during the early Holocene warm period, which was a period of enhanced drought and increased summer warmth, particularly from ca. 10,500-8000 cal yr BP (Walker and Pellatt, 2008). Fire frequency then increased somewhat at Doheney Lake during the next four millennia as the climate cooled and moistened. Perhaps the only portion of the fire frequency curve that seems to make more sense in terms of climate is the late Holocene, which is generally described as a stable but cool and moist period (Walker and Pellatt, 2008). Fire frequency at Doheney Lake decreased during this interval until ca. 1200 cal yr BP, after which it increased until present, which is not really explained by known broad-scale climatic shifts.

It appears instead that fire activity at Doheney Lake more closely tracked climate-induced vegetation shifts during the Holocene, which affected available burnable biomass. Charcoal concentrations and CHARs increased after ca. 8000 cal yr BP as *Pseudotsuga/Larix* increased in abundance and the modern-day forest established (Figs. 5 and 6). Fire regimes in the late Holocene, however, are still difficult to explain given that climate was thought to be relatively stable (Walker and Pellatt, 2008) and forest composition varied little. It appears instead that during the late Holocene shifts in fire activity, particularly increased CHARs between ca. 3500-1600 cal yr BP, drove changes in forest structure (as described above).

As opposed to millennial-scale climatic influences, fire regimes at Doheney Lake may have been driven by changes in interannual variability, such as those created by the Pacific Decadal Oscillation (PDO) and El Niño-Southern Oscillation (ENSO). Numerous studies show a strong link between drought conditions and ENSO and/or PDO in the interior PNW, including research conducted from nearby Castor Lake (Nelson et al., 2011). Other studies also link increased fire activity in the interior PNW with drought years associated with specific phases of the PDO and ENSO (Hessl et al., 2004; Heyerdahl et al., 2008). Increased CHARs during the middle and late Holocene at Doheney Lake generally coincide with the general upward trend of ENSO events from 8,000 cal yr BP to present (Moy et al., 2002). It may be that similar to the desert southwest (SW) of the US, cooler wetter years provided the conditions necessary for fine fuel growth at Doheney Lake, while subsequent warmer drier years allowed that biomass to burn (Grissino-Mayer and Swetnam, 2000). The phases, however, are opposite from those experienced in the SW.

If large-scale or regional climatic fluctuations were driving the changes in fire activity at Doheney Lake during the postglacial period, either directly or through climate-induced vegetation changes, then nearby reconstructions should show similar trends. However, few fire history reconstructions exist with which to compare to the Doheney Lake record. Brown et al. (2017) reconstructed fire history for the past ca. 8500 years at Scum Lake located in a *P. contorta*-dominated forest on the Chilcotin Plateau (British Columbia). Both the Scum and Doheney lakes records show corresponding trends of increased CHARs from ca. 5500 cal yr BP to just after 2000 cal yr BP. Following this, both records show a gentle decrease in CHARs to 1000 cal yr BP, where they both increased slightly until Euro American settlement. At this point, CHARs at Doheney Lake sharply declined to the end of the record, where as they remained high at Scum Lake. It is worth noting that though the CHAR curves share a similar shape, the fire frequencies curves differ greatly. Fire frequencies are highest at Scum Lake after ca. 3000 cal yr BP, while frequencies are lowest at Doheney Lake at this time. This could be because CharAnalysis does a better job identifying fire episodes at Scum Lake, which exists within a moderate-severity fire regime, so the record is “peakier” (Brown et al., 2017).

Also available for comparison is a 3800-year long record from nearby Fish Lake, which is situated approximately 3 km NW of Doheney Lake within the SWA (Fig. 1; Walsh et al., in press). The reconstructions bear little resemblance to one another from ca. 3800-1200 cal yr BP, with seemingly more frequent low-severity fires occurring at Fish Lake at this time, and less frequent higher severity fires occurring at Doheney Lake, indicated by the slightly lower proportion of herbaceous charcoal (Fig. 7). This is likely because Fish Lake had less forest and more sagebrush steppe, which today exists on the south-facing shore of the lake, during this interval. However after ca. 1200 cal yr BP both records show a general increase in CHAR, with lower fire activity during the MCA and higher during the LIA. While the peak of the CHAR curves are similar in shape, the timing of them is slightly off (ca. 275 cal yr BP at Doheney Lake and ca. 175 cal yr BP at Fish Lake), which could be due to constraints on the age models. Both reconstructions show a steep decline in CHARs after those respective peaks, with almost no charcoal accumulation into either record after ca. 50 cal yr BP (AD 1900). Increases in *Pseudotsuga/Larix* at both sites at this time indicate the start of anthropogenic fire suppression, which likely included the loss of both human-set and lightning-ignited fires (discussed in further detail below).

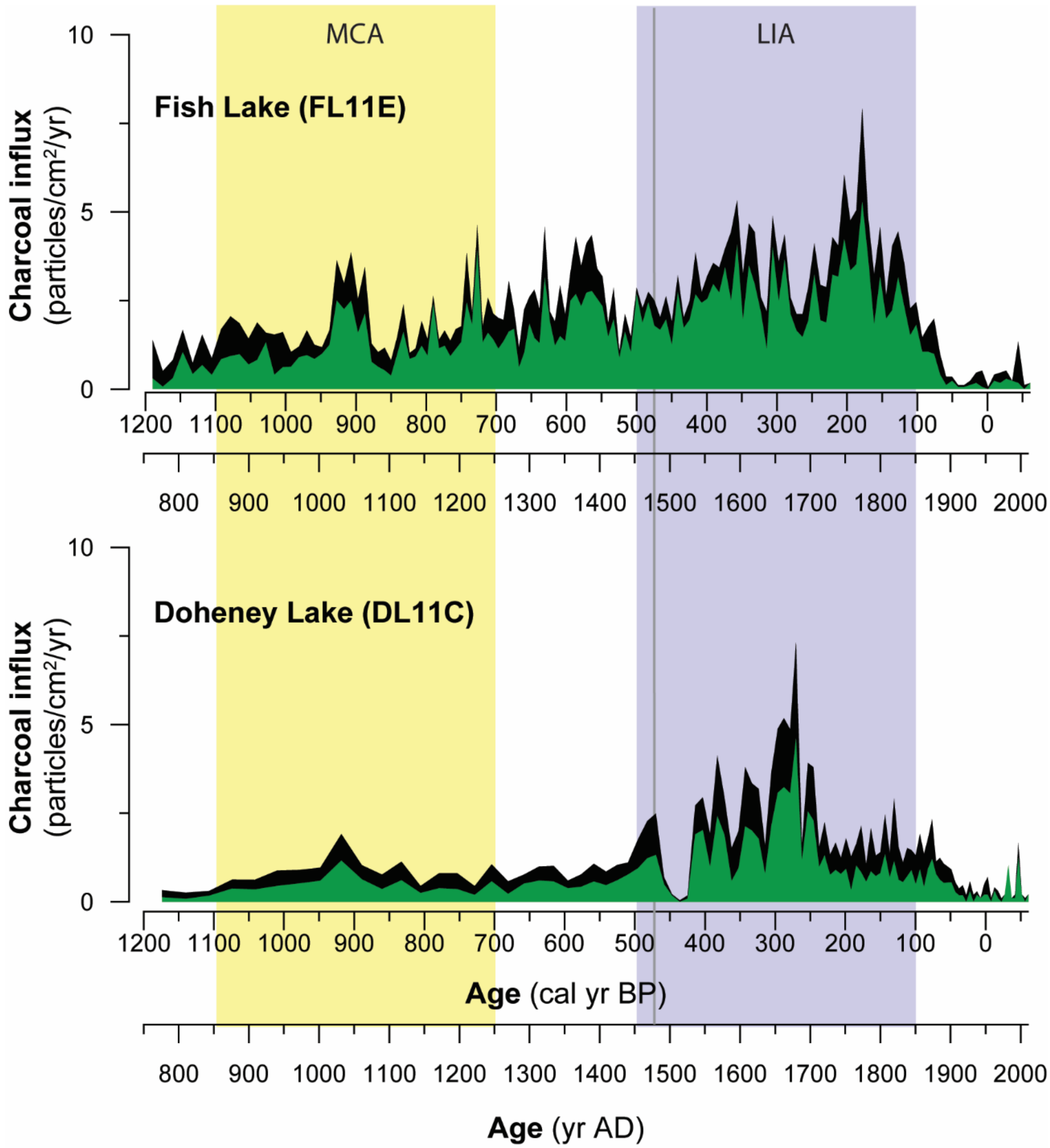

Fig. 7. Comparison of charcoal influx (CHAR; particles/cm^2/yr) for Fish Lake (FL11E) and Doheney Lake (DL11C) cores. The green curves indicate the proportion of herbaceous charcoal. Vertical gray bar indicates the depth of the MSH-W tephra layer.

It is also necessary to consider the likelihood that human use of fire contributed to the observed fire regimes at Doheney Lake during the postglacial period. Humans have been present in the interior PNW since ca. 12000 cal yr BP (Baker, 1990), however archaeological evidence suggests that populations were not of considerable size until after ca. 5000-4000 cal yr BP (Ames, 2000). Increased population size may be what is reflected in the Doheney Lake CHAR curve, as humans would have more intensely used fire as a plant management tool and to manipulate forest cover (Turner, 1999). The area in and around the SWA was the ancestral homeland of the Sinkaietk (Southern Okanogan), and some evidence of prehistoric human use of the area remains on the landscape today in the form of culturally-modified trees and remnants of pit houses (Oliver, 2014). Unfortunately there is little documentation indicating use of fire by the native people in the SWA. However, fire was a known land management tool used by the nearby Colville tribe (see Boyd, 1999), which makes it likely that it was used in the SWA as well (see Walsh et al., in press for further discussion). This may be a possible explanation for the highly variable CHARs during the late Holocene that appear to be asynchronous with climatic shifts such as the Medieval Climate Anomaly (MCA; 1100-700 cal yr BP) and Little Ice Age (LIA; 500-100 cal yr BP) (Fig. x).

Section 3: Pre- versus Post-Euro American Settlement Fire Regimes in SWA

Fire regimes in the SWA shifted dramatically following Euro American settlement at ca. 100 cal yr BP (AD 1850) as Native Americans were removed from the landscape (either by disease or forceful relocation) and fire suppression policy became widespread. The impact of this is clear when looking at fire data from the Okanagan-Wenatchee National Forest for the past century, which shows that very few fires burned from the 1930s-1980s (Fig. 8). Work by Schellhaas et al. (2009) reveals the effects of local fire suppression on stand composition and forest structure in the SWA. They documented that trees per hectare have increased dramatically with the majority of this occurring in the small diameter class. Additionally, most stands have shifted from ponderosa pine-dominated to Douglas-fir-dominated. Similarly, Haeuser (2014) illustrated encroachment patterns in the SWA supported by aerial and historical photos, where she noted that as a result of 20th century fire suppression, ponderosa pine has encroached into the lower elevation shrub steppe portions of the SWA, and Douglas-fir has encroached into ponderosa pine stands. This overstocking resulting from fire suppression has effectively changed the fire regime of the SWA, similarly to the surrounding Okanogan-Wenatchee National Forest (Fig. 8). Fire suppression has been so successful that it has shifted fire regimes in eastern cascade dry forest to a low frequency, high-severity regime. For the SWA, and Okanogan County, this culminated in the 2015 fire season where the Okanogan Complex Fire burned over 121,000 hectares, including the Doheney Lake watershed (Fig. 2).

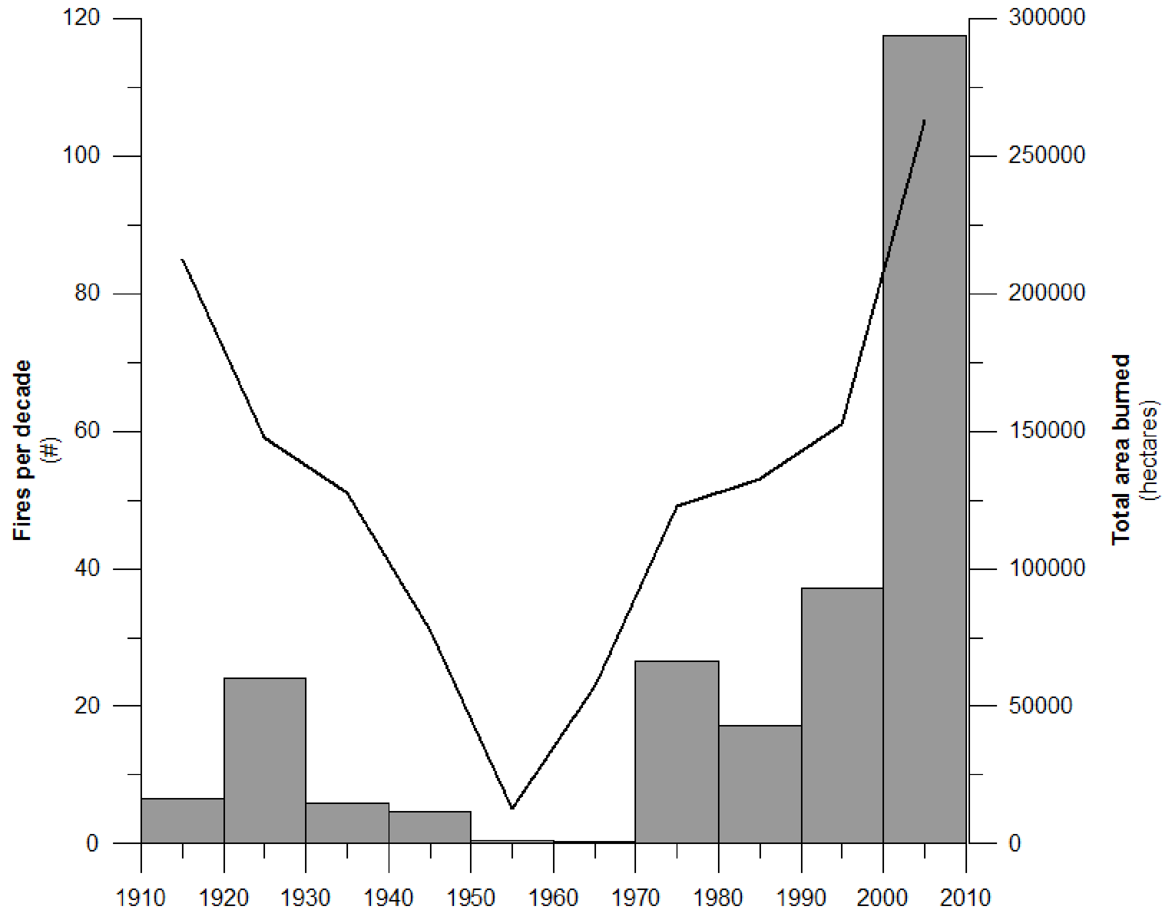

Fig. 8. Fires per decade (black line) and total area burned (gray bars) in the Okanagan-Wenatchee National Forest between 1910 and 2010. Data source: Okanagan-Wenatchee National Forest Fire and Aviation Dataset (2012).

VI. Conclusions

While the Doheney Lake record does provide insight into the postglacial environment in the SWA, it also brings forth questions left unanswered at this time. The trends in the vegetation establishment and shifts are generally supported by existing studies, yet the fire history does not conform to the theory that climate has been the primary driver of fire activity in this ecosystem during the postglacial period. This partially stems from the seemingly inverse relationship between the CharAnalysis fire frequency results and CHAR, as well as what are uncharacteristically long fire return intervals for this environment during the late Holocene. This may be explained by CharAnalysis' limitations when it comes to analyzing a record with high charcoal accumulation rate and relatively low temporal resolution. With this in mind, the record seems to suggest that cooler and moister periods during the middle and late Holocene along with a more forested environment allowed for more burning to occur on the landscape. Overall, when compared alongside the vegetation history, the CHAR record suggests that fire on the landscape was primarily driven by fuel availability. It is unclear to what degree humans affected this fire history prior to the period of Euro American settlement, however there is a correlation between increased CHARs and what are believed to be increasing human populations during middle to late Holocene (after ca. 5500 years).

Based on this reconstruction, it is clear that fire has been a constant presence on the landscape from the time of deglaciation until the start of Euro American settlement. It is likely that fire in the SWA will continue to be driven by fuel availability. Recent catastrophic fire seasons during drought years in the area demonstrate that humans can only suppress fire, not eradicate it, especially given current fuel conditions. It may be beneficial for management agencies to consider further use of fire in the SWA as a management tool.

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